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Technology & Mechanics Overview of Air-Inflated Fabric Structures

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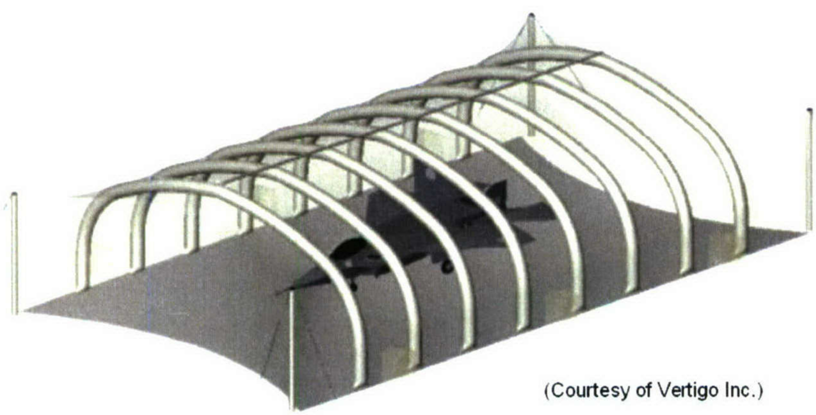
INTRODUCTION:

Air-inflated fabric structures are categorized as pre-tensioned structures and are uniquely capable of many advantages not available with traditional structures. These include lighter weight designs, rapid and self-erecting deployments, enhanced mobility, large deployed-to-packaged volume ratios, fail-safe collapse and optional rigidification.

Research and development in pursuit of air-inflated structures can be traced to space, military, commercial and marine applications. Examples include air ships, weather balloons, inflatable radomes, shelters, pneumatic muscles, inflatable boats, bridging, and energy absorbers such as automotive air bags and landing cushions for space vehicles. Recent advances in high performance fibers and improved textile manufacturing methods have fostered emerging interests in air-inflated fabric structures which are increasingly designed as reliable alternatives to conventional structures. Several examples demonstrating substantial load-carrying capacities and self deployment are shown (Figs 1-4).



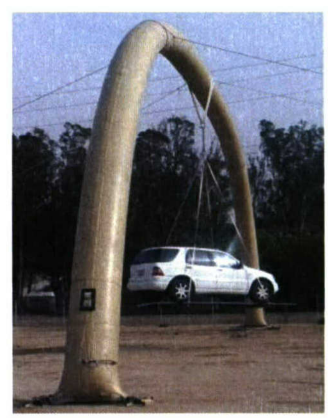
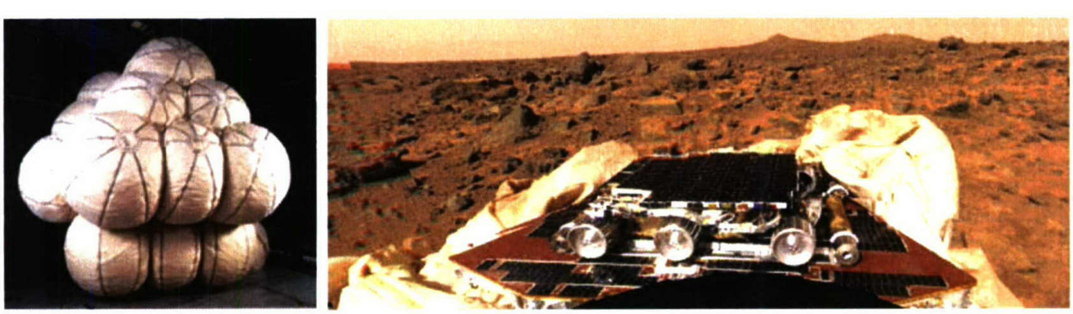


Fig 1. Inflated fabric arches used in aircraft shelters (left); Demonstration of arch load-carrying capability (right).



(Courtesy of ILC Dover Inc.)

Fig 2. Impact Attenuation System for Mars Pathfinder.

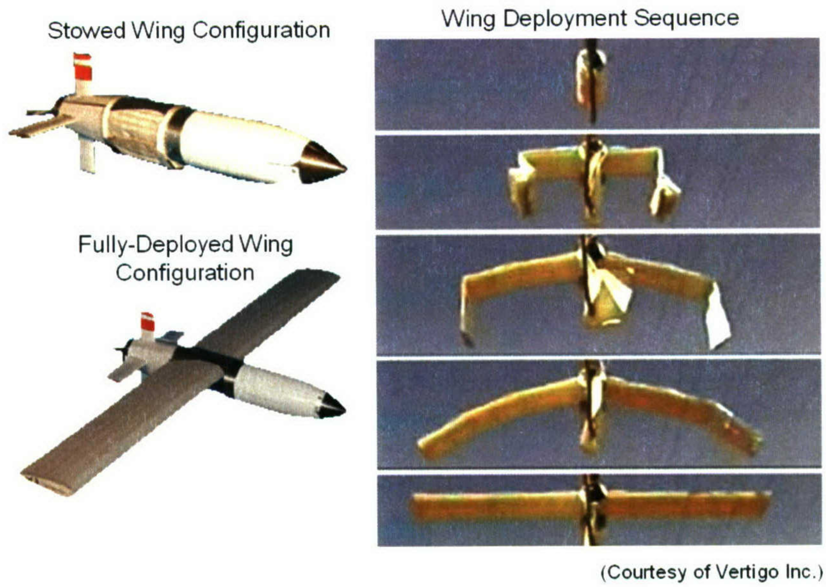


Fig 3. Inflatable wings on a gun-launched observation vehicle.

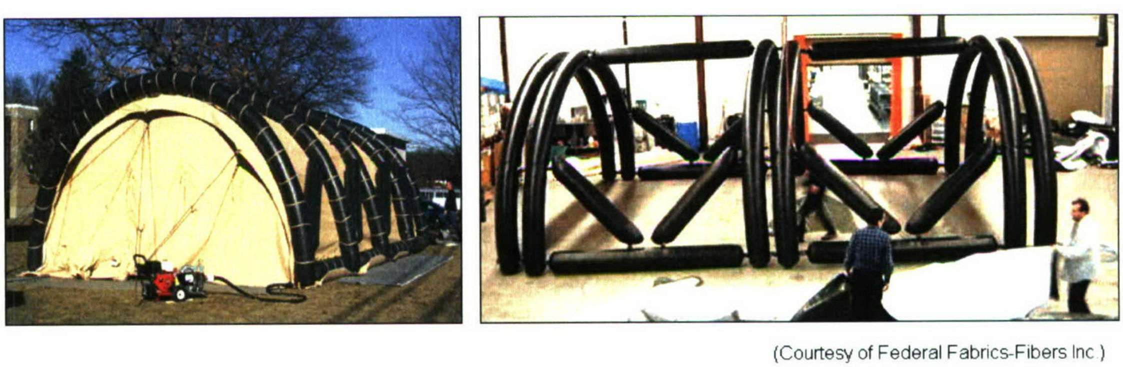


Fig. 4. Shelter constructed with a self-deploying woven fabric air beam system.

DESCRIPTION:

Air-inflated fabric structures are constructed of lightweight fabric skins, internal elastomeric bladders, inflation valves and optional pressure relief valves. The bladder contains the air and transfers the pressure to the fabric. Once sufficiently pressurized, the fabric becomes pre-tensioned providing the structure with a plurality of stiffnesses including axial, bending, shear, and torsion.

Fabrics in air-inflated structures are typically formed from textile architectures (Fig. 5). Each architecture has its own design, manufacturing and performance advantages and their responses to applied forces vary. The weave develops extensional stiffness when tensile force F_y is applied but lacks rotational stiffness when shear force F_x is applied. On the contrary, braided

fabrics generate rotational stiffness in the presence of F_x but lack extensional stiffness in the presence of F_y. Here, θ is referred to as the braid or bias angle. The triaxial braid and strap-reinforced braid architectures afford both extensional stiffness when loaded with F_y and rotational stiffness when loaded with F_x.

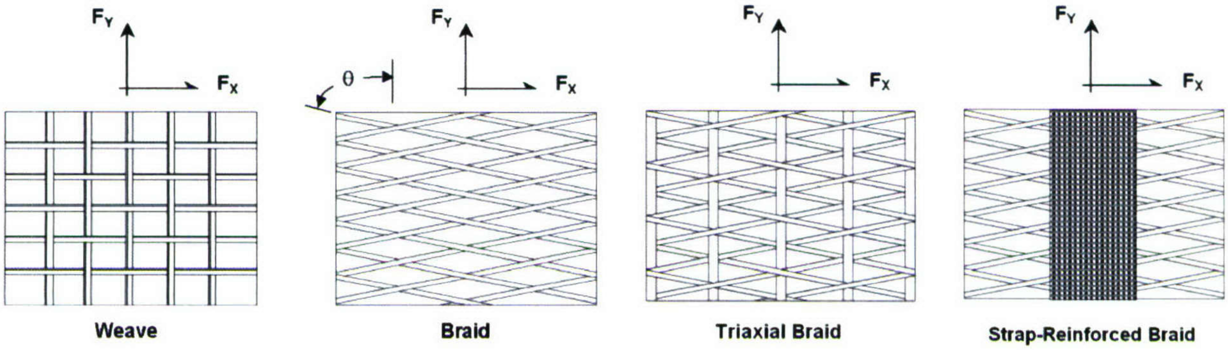


Fig. 5. Textile architectures used in air-inflated fabric structures.

During inflation, the bladder expands until resisted by the fabric. A biaxial pre-tensioning stress develops in the fabric enabling the structure to achieve static equilibrium. The pre-tension stress allows the structure to generate its intended shape, stiffness to resist deformations and stability against collapse from external forces. Stiffness of the structure is primarily a function of inflation pressure.

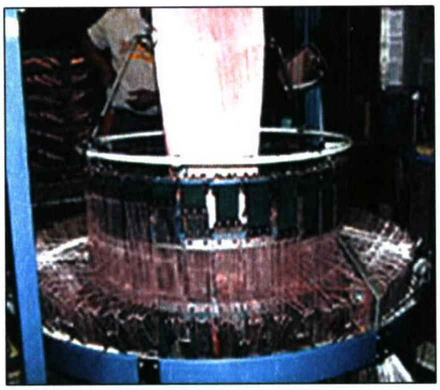
Upon application of external forces, a redistribution of stresses occurs to balance the forces and maintain equilibrium. Stability is ensured when no regions of the fabric experience a net loss in tensile stress. Otherwise, wrinkling will occur which decreases the structure's load carrying capability. Continued loading of a wrinkled structure will ultimately lead to collapse. Of the unique advantages afforded by inflated fabric structures, two relate to stability. First, a collapse does not necessarily damage the fabric. When an overload condition is removed, the structure may restore itself to its original configuration. This is referred to as fail-safe collapse. Second, since wrinkling can be visually detected, it can serve as a warning indicator prior to collapse.

YARN FIBERS:

Many of today's fabric structures use yarns constructed of high performance continuous fibers such as Vectran® (liquid crystal polymer), PEN® (polyethylene naphthalate), DSP® (dimensionally stable polyester), etc. These fibers provide high strength, low elongation, high flex-fold fatigue, low creep and enhanced environmental resistance to ultraviolet rays, heat, humidity, moisture, abrasion, chemicals, etc. Other fibers used include Kevlar®, Dacron®, nylon, Spectra® and polyester.

CONTINUOUS MANUFACTURING AND SEAMLESS FABRICS:

Prior to the continuous circular weaving and braiding processes available today, air-inflated fabric structures were constructed using adhesively bonded, piece-cut manufacturing methods. These methods were limited to relatively low pressures because of fabric failures and air leakage through the seams. Continuous circular weaving and braiding processes can eliminate or minimize the number of seams resulting in improved reliability, significantly higher pressures limits and greater load-carrying capacities (Fig. 6).



(Courtesy of Federal Fabrics-Fibers Inc.)

Continuous Circular Weaving

(Courtesy of Vertigo Inc.)

Braiding

Fig. 6. Continuous manufacturing methods.

IMPROVED DAMAGE TOLERANCE:

Assorted methods are used to enhance the reliability of air-inflated fabric structures against various damage mechanisms. Resistance to punctures, impacts, tears and abrasion can be improved by using high-density weaves, rip-stop constructions and coatings. High-density weaves are less susceptible to penetrations and provide greater coverage protection for bladders. Rip-stop fabrics have periodic inclusions of high tenacity yarns woven in a cellular arrangement (Fig. 7). (The breaking strength of a yarn is referred to as tenacity which is defined in units of grams-force per denier. Denier is a mass per unit length measure expressed as the mass in grams of a 9,000 meter long yarn.) The high tenacity yarns contain fractures of the basic yarns and prevent fractures from propagating across cells.

Additionally, coatings protect the fabric against environmental exposure to ultraviolet rays, moisture, fire, chemicals, etc. Coating materials such as urethane, PVC (poly vinyl chloride), neoprene, EPDM (ethylene propylene diene monomer) are commonly used. Additives such as Hypalon® further enhance a coating's resistance to ultraviolet light and abrasion. Coatings generally increase the extensional and rotational stiffnesses of the fabric but remain sufficiently flexible to not adversely impact stowage operations of the structure.

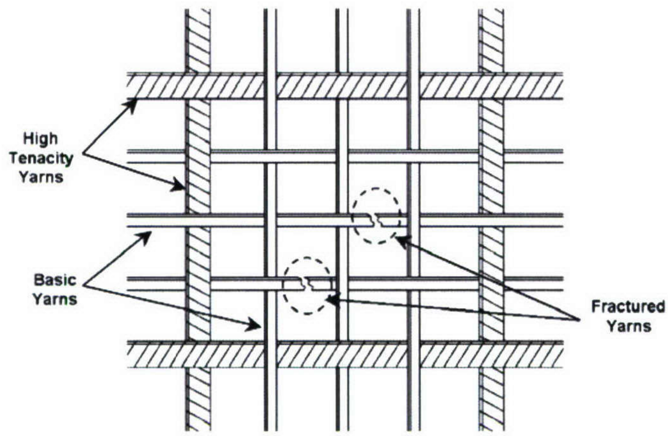


Fig. 7. Rip-stop fabric architecture.

RIGIDIFICATION:

Air-inflated fabric structures can be rigidified through the use of coatings such as thermoplastics, thermosets, and shape memory polymers. Prior to inflation, these coatings are applied to the fabric and remain initially uncured. After the structure is inflated and properly erected, a phase change is triggered in the coating by a controlled chemical reaction (cure process) activated by exposure to elevated temperature, ultraviolet light, pressure, diffusion, etc. Once the phase change is fully developed, the coating binds the yarns together, stiffens the fabric in tension, compression and shear, and behaves similar to a matrix material found in traditional fiber-reinforced composites. The fabric structure is now rigidified and no longer requires inflation pressure to maintain its shape and stiffness. Depending upon the coating used, the transition process may be permanent or reversible. Reversible rigidification is especially suited for applications requiring multiple long-term deployments. The rigidified structure may, however, have different failure modes than its pressurized counterpart including shell buckling and compression rather than wrinkling. Rigidification is of particular interest for space structures because of restrictions on payload volumes. Shape memory composites are a current focus for rigidizing deployable space frames.

DROP-STITCHED FABRICS:

Drop-stitch technology, originally pursued by the aerospace industry, extends the shapes that air-inflated fabric structures can achieve to include flat and curved panels with moderate to large aspect ratios and variable thickness. Drop-stitched fabric construction consists of external skins laminated to a pair of intermediate woven fabric layers separated by a length of perpendicularly aligned fibers (Fig. 8). During the weaving process of the intermediate layers, fibers are dropped between the layers. Upon inflation, the intermediate layers separate forming a panel of thickness controlled by the drop-stitched fiber lengths. Flatness of the inflated panel can be achieved with a sufficient distribution of drop-stitching. The external skins can be membranes or coated fabrics which serve as impermeable barriers to prevent air leakage, thus eliminating the need for a separate bladder. Air-inflated structures incorporating drop-stitched

fabrics include floors for inflatable boats, energy absorbing walls, temporary barriers, lightweight foundation forms, and most recently, an inflatable body armor system.

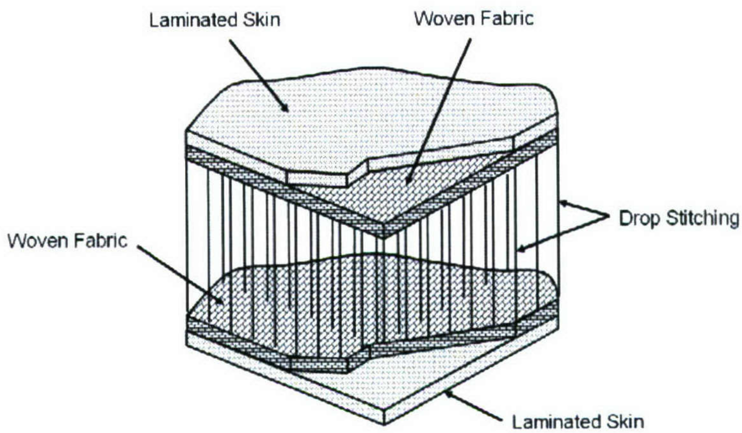


Fig 8. Section view of a drop-stitched fabric.

AIR BEAMS:

Air beams are fundamental examples of inflated structures and are constructed of fabric skins with internal bladders (Fig. 9). They support a variety of loads similar to conventional beams. Seamless air beams have been constructed using continuous manufacturing methods achieving diameters up to 42 inches (1.07 m). Air beams have circular cross sections and their lengths can be straight, tapered or curved such as an arch. The ends are closed using various end termination methods such as bonding, stitching, clamping, etc. depending upon pressure and loading requirements.

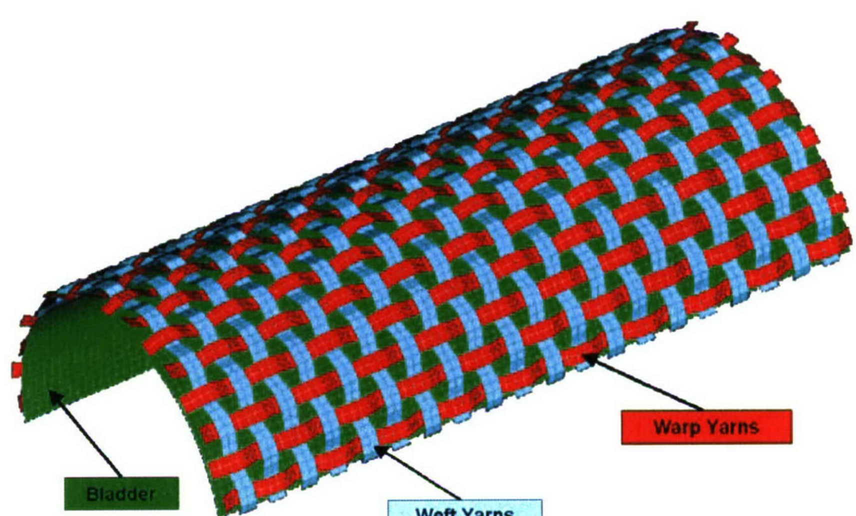


Fig 9. Partial section view of a woven air beam.

In woven air beams, the warp yarns are aligned on the longitudinal axis to resist longitudinal forces and bending moments. The weft yarns spiral through the weave nearly 90° to the warp yarns, thus lying along the hoop direction. Weft yarns provide stability against collapse by maintaining the circular cross section. Once pressurized, the weft yarn tension per unit length of air beam equals *Pr*, where *P* is the pressure and *r* is the radius. The warp yarn tension per unit circumference equals *Pr/2*. Hence, the ratio of hoop (cylindrical) stress per unit length to the longitudinal stress per unit circumference is 2:1.

Now, consider a woven air beam subjected to bending. The pre-tension and bending forces superimpose such that compressive bending forces subtract from the pre-tension forces while tensile bending forces add to the pre-tension forces. The instant any point along the air beam develops a zero net longitudinal tensile stress, the onset of wrinkling has occurred. The corresponding being moment is the wrinkling moment, M_w. Once wrinkling develops, the moment-curvature relationship behaves nonlinearly. With further loading, the cross section loses bending stiffness and eventual collapse follows. The spread of wrinkling around the circumference is similar to the flow of plasticity in metal beams subjected to bending.

The wrinkling moment, derived from a simple balance of the longitudinal stresses due to inflation and bending, is shown in Eq. (1) and is valid only for woven air beams. Note that M_w is independent of the fabric properties.

$$M_W = \frac{P\pi\, r^3}{2}, \qquad (1)$$

where: P = inflation pressure
r = radius.

Laboratory testing of a 6.0-inch (15.24 cm) diameter woven fabric air beam was conducted using a 4-point bend arrangement and force versus mid-span deflection results were collected to demonstrate the influence of pressure on bending behavior (Fig. 10).

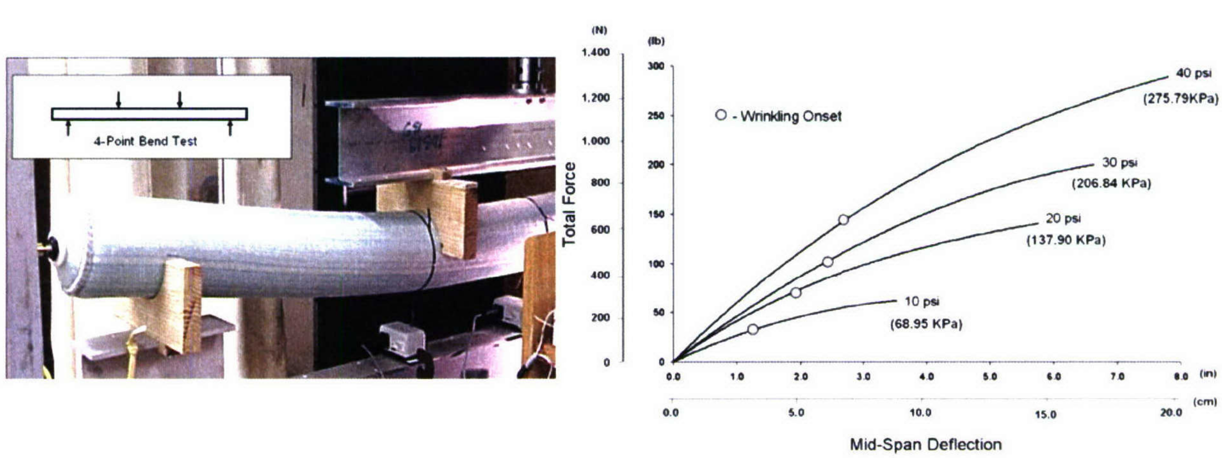


Fig 10. 4-Point bend test of a 6.0-inch (15.24 cm) diameter woven fabric air beam.

EFFECTS OF AIR COMPRESSIBILITY:

The load-deflection response may depend upon stiffening sources other than initial inflation pressure. If appreciable changes in pressure or volume occur, as for energy absorbers, work is performed on the air through compressibility. Air compressibility can be modeled from thermodynamic principles according to the Ideal Gas Law of Eq. (2).

$$P\,V = mRT\,, \tag{2}$$

where: P = absolute pressure
V = volume
m = mass of air
R = gas constant for air
T = absolute temperature (°K).

For a quasi-static, isothermal process, the work done on the air is:

$$W_{air} = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{mRT}{V} dV = m\,R\,T \ln \frac{V_2}{V_1}\,. \tag{3}$$

The total energy, E_{total}, is the work done by external forces, W_{ext}, which is related to the total strain energy of the fabric, U_f, and W_{air} as shown in the energy balance of Eq. (4).

$$E_{total} = W_{ext} = U_f + W_{air}\,. \tag{4}$$

If volume changes are large, U_f may be negligible, W_{air} will dominate the energy balance and deflections can be readily computed.

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See also: Inflatable Structure, Pressure Stabilized Structure, Tensioned Structure, Textile, Fabric Mechanics.

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